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Sustainable polypropylene chair: A life cycle assessment and cost analysis of industrial production

Lucrezia Maggi[1] | Alberto Pietro Damiano Baltrocchi[1,2] | Marco Carnevale Miino[1] | Elena Cristina Rada[1] | Vincenzo Torretta[1]

[1]Department of Theoretical and Applied Sciences, University of Insubria, Varese, Italy
[2]Department of Science and High Technology, University of Insubria, Como, Italy

Correspondence
Lucrezia Maggi, Department of Theoretical and Applied Sciences, University of Insubria, Via O. Rossi 9, Varese I-21100, Italy.
Email: lmaggi1@studenti.uninsubria.it

Abstract

Due to their multiple properties, including flexibility, lightness, and strength, thermoplastics are an essential material in the development of processes at both industrial and domestic levels. However, thermoplastics are often derived from polymers synthesized using non-renewable petroleum resources. This has environmental consequences. The following research is proposed as the first environmental and economic impact evaluation of the extrusion and molding process of polypropylene (PP) generated by an industrial site for monobloc plastic chair production, through a Life Cycle Assessment (LCA) and Cost Analysis (CA) methodology. The analysis was conducted using SimaPro v10.1 software, Ecoinvent v3.10 database, and ReCiPe 2016 v1.07 impact assessment method. This study proposes multiple mitigative scenarios applicable to reduce the business-as-usual impact. Primary data was collected in 2024. The results show a significant environmental impact reduction caused by the substitution of the virgin PP with the recycled PP (−39%), a lower one generated by the substitution of the Italian country energy mix with the adoption of renewable energy sources (−12%), and a global added reduction obtained summarizing the two alternatives (−55%). The economic impacts are, instead, slightly influenced by the change in input raw materials, due to similar market costs. However, the cost reductions associated with the change in energetic source can be considered not negligible, excluding the plant design and commissioning costs. This research provides decision-makers with valuable guidance for implementing PP production plants, promoting sustainability and a circular economy. Advancing these prerogatives supports the achievement of Sustainable Development Goals, particularly SDGs 3, 11, and 13.

Abbreviations: BAU, business as usual; BO, best option; CA, cost analysis; ES, ecosystem; FET, freshwater eutrophication; FEX, freshwater ecotoxicity; FPM, fine particulate matter formation; FRS, fossil resources scarcity; FU, functional unit; GWP, global warming potential; HCT, human carcinogenic toxicity; HCNT, human non-cancerogenic toxicity; HH, human health; LCA, life cycle assessment; LCI, life cycle inventory; LU, land use; MET, marine eutrophication; MEX, marine ecotoxicity; MRS, mineral resources scarcity; OFH, ozone formation, human health; OFT, ozone formation, terrestrial ecosystems; PA, polyamide; PCR, product category rules; PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PS, polystyrene; Pt, point; PVC, polyvinyl chloride; RE, resources; RES, renewable energy scenario; S, substitution; SB, system boundaries; S-LCA, social life cycle assessment; SOD, stratospheric ozone depletion; TET, terrestrial acidification; TEX, terrestrial ecotoxicity; WC, water consumption; USD, United States dollars.

KEYWORDS
circular economy, environmental impacts, life cycle assessment, life cycle costing, polypropylene, sustainable process

1 | INTRODUCTION

Plastics are essential materials across various industrial sectors, including construction, transportation, packaging, and medical technologies. Plastic's involvement in a broad range of applications is attributed to three key factors: its versatility, lightweight properties, cost-effectiveness, and durability. These characteristics have a strong influence on human lifestyles [1,2]. The significant role of plastic in our daily life has also been recognized by the Environmental Protection Agency [3]. The global production of plastics reached 400.3 million tonnes in 2022, with China and the North American Free Trade Agreement (NAFTA) region accounting together for more than 50% of the total production [4]. Europe represents a substantial portion of global plastic production, contributing 15% of the total output, and the average annual per capita consumption of plastics is approximately 150 kg, nearly twice the global average of 60 kg [4,5]. This surge in plastic production is accompanied by an increase in plastic waste, which presents considerable environmental, ecological [6,7], social [8], and economic challenges [9]. As highlighted in Erikson et al. [10], understanding the impacts of plastic resins like PP from cradle to gate helps define baseline emissions and resource use, which is useful for comparison across sectors.

Thermoplastics account for approximately 90% of global plastic production [11]. Their formability and low density make them suitable for a wide array of applications, particularly in the design and manufacturing of industrial products. Polyamide (PA), polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) represent the most common polymers of thermoplastics [12,13]. However, their environmental impact is evident throughout their entire life cycle, encompassing raw material extraction, transportation, manufacturing, and waste management [14,15]. Patel et al. [16] emphasize the potential of both mechanical and chemical recycling to reduce these impacts, though trade-offs in emissions and efficiency remain.

Among the different polymers, PP exhibits several key properties, including strength, flexibility, stability, and lightness [17]. Thanks to its high melting point (160°C), PP can withstand continuous use at elevated temperatures and is commonly used in applications such as hot-filled and microwavable packaging. This polymer is highly versatile, offering adaptability in various shapes, structures, and stiffness levels [18]. The synthesis of PP is often followed by a thermoforming process, which allows the polymer sheets to be molded into the desired shapes. The primary application of PP lies in the packaging industry, particularly in food packaging (e.g., yogurt jars and margarine tubs), snack wrappers, hinged caps, and microwave containers. Additionally, PP is utilized in the production of pipes, automotive parts, and banknotes [4].

PP is a petroleum-based thermoplastic, and like other such materials, it is associated with various environmental impacts. Therefore, some biomaterial-based PP has been developed and studied [19].

The use of recycled PP can lead to a significant reduction in the use of virgin PP, mitigating the environmental impacts, such as limiting soil pollution, greenhouse gas emissions, and waste production [20]. However, despite these advantages, PP recycling often faces challenges due to the high levels of impurities present in recycled materials. Removing these impurities requires sophisticated techniques, which are typically expensive and can have an environmental impact [21]. For this reason, to enhance environmental sustainability, it could be more feasible to reduce emissions during production.

As previously discussed, plastics can be used for multiple applications. To better estimate the environmental impact of a product or process, a life cycle assessment (LCA) can be conducted to provide data on the specific environmental impacts of the industrial process [22–24]. LCA is an internationally standardized methodology based on ISO 14040-44 [25,26]. Baltrocchi et al. [27] applied real industry data in LCA of recycled polyamides, demonstrating how using measured values instead of assumptions significantly improves accuracy.

The number of studies addressing the LCA of PP molding processes remains limited. Existing research mainly focuses on comparing PP with alternative materials in various applications. For example, Cui et al. [28] assessed the environmental impacts of traditional plastic takeaway boxes and their substitutes. Zhao et al. [29] conducted an LCA on an automotive interior component using BF/nano-talc/PP composites, further optimized by Li et al. [30]. Skinner et al. [31] compared three bio-based food punnets with conventional PP versions. Yahyapour et al. [32] evaluated different automotive materials, including PP. Ansari Movahed et al. [33] compared PHB and PP composites reinforced with CNCs, while Bakshi et al. [34] investigated PP and LDPE composites reinforced with calcium-rich industrial waste. Mannheim [35] examined three scenarios involving homogeneous PP and mixed plastics. Deng et al. [36] analyzed fiber-reinforced PP in automotive contexts, and Korol et al. [37] studied plastic pallets made from bio-composites and various PP-based composites. While these studies emphasize material comparisons (particularly in automotive, packaging, and pallet applications), a comprehensive LCA addressing the whole production cycle, including extrusion and molding, is still lacking. To the best of the authors' knowledge, no previous research has explicitly conducted a full-scale LCA focusing on the extrusion and molding stages of PP, despite their widespread industrial relevance. This work, therefore, addresses a significant gap in the literature, offering a unique contribution through its integrated analysis of these production phases.

While studies in the existing literature on extrusion-related PP have focused on optimizing the material itself, exploring chemical, mechanical, and biological solutions to improve its efficiency and sustainability, the novelty of this study lies in proposing an analysis of PP as a material component of a production process, which can be improved through direct substitution. This approach represents a shift in perspective: rather than aiming to enhance the polymer itself, the study investigates how its integration into a production system can be optimized from an environmental standpoint. This distinction introduces a novel process-centered lens into the discourse on PP sustainability. Consequently, this study does not aim to analyze PP as a material that can be improved; instead, it aims to understand how to enhance a production process that incorporates PP. The study encourages a transition from a material-focused to a process-focused sustainability assessment—an aspect that remains underexplored in the existing literature.

This work aims to fill this gap by conducting an LCA of the extrusion and molding processes associated with a PP chair model. Most studies on the LCA of PP focus on materials research and development. In contrast, based on the authors' knowledge, this is the first attempt to investigate the use of this virgin and/or recycled material in a production system. The analysis encompasses a comprehensive evaluation of the raw material inputs and the energy inputs from the process itself. This evaluation not only assesses the viability of PP as a material for implementation but also explores its potential as a component of a more extensive and variable system, such as the technical production system. This assessment has the potential to provide novel insights into this significant and global production domain. It will express the environmental and economic impacts of a leading raw material in the thermoplastics industry in the form of actual impacts.

2 | MATERIALS AND METHODS

2.1 | Goal and scope of the study

The objective of the present study is to assess the sustainability of the investigated production process by evaluating its environmental impact, outputs, and economic findings. To assess the environmental dimension, an LCA was used, while for the economic aspect, a qualitative analysis of market prices of substances and sub-processes was conducted, which will be referred to hereafter as Cost Analysis (CA).

For both LCA and CA, the Functional Unit (FU) refers to 1 chair, and a cradle-to-gate System Boundaries (SB) approach was followed, as schematically illustrated in Figure 1.

The scheme of the LCA section of the research followed the Product Category Rules (PCR) 2010:16 Plastics in primary forms v4 [38]. One Pt is directly proportional to the environmental impact of one EU citizen per year (100 Pt = the impact of 1 EU citizen per year). It serves as the measurement unit for the normalized environmental impacts of a unit, product, or material [39]. As reported in the PCR, the life cycle was divided into two phases: upstream and core.

The LCA study seeks to:

i. Quantify the aggregate environmental impacts associated with the production of a PP chair.
ii. Conduct an impact analysis by production process and/or input material.
iii. Carry out an impact analysis by macro impact endpoint category.

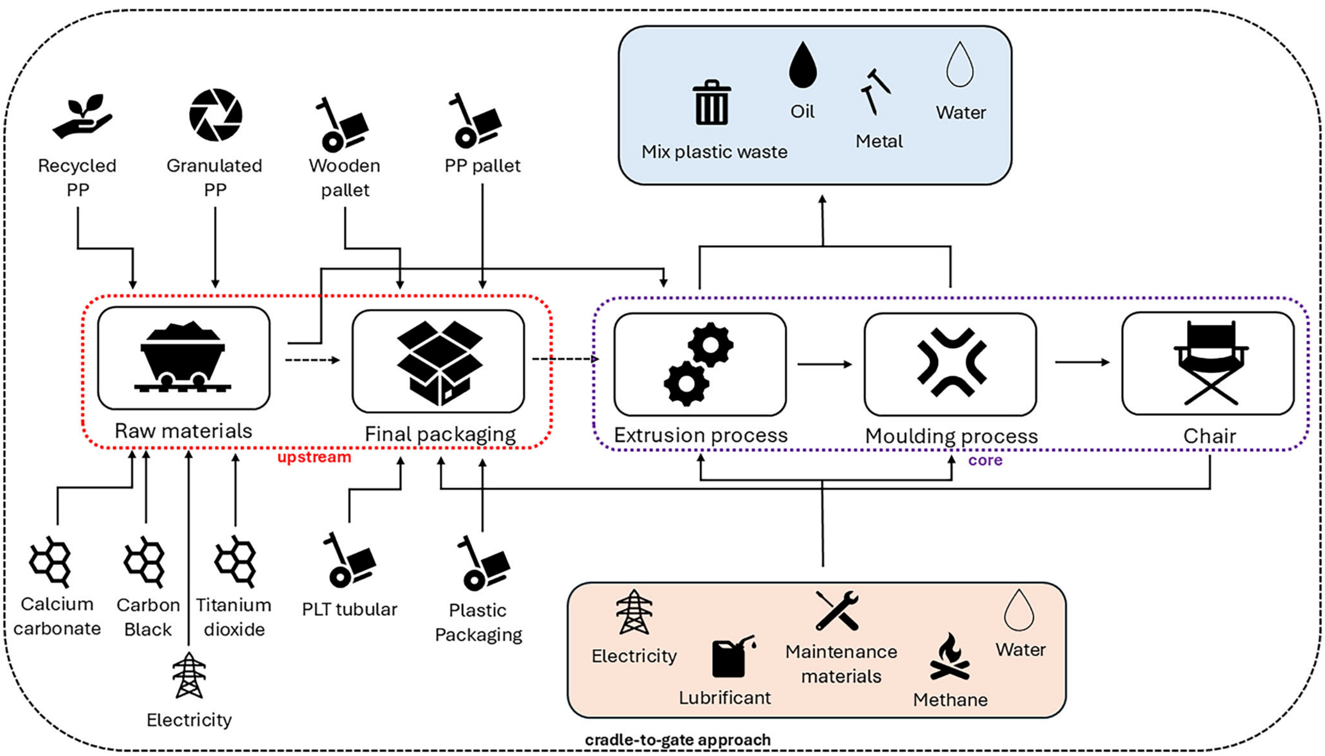

FIGURE 1 System Boundaries for the LCA and CA.

iv. Compare the values obtained and identify the most effective solution for impact reduction.

The CA was carried out according to the framework of the LCA. The economic analysis wants to answer two main questions:

i. Which is the most expensive phase of the analysis?
ii. Which material or process generates a higher cost for each phase?

Regarding inventory analysis, the cost ranges or average data collected are reassessed, and considering the average values, these have been associated with the FU. The LCA was performed using SimaPro v10.1 software [40] and the Ecoinvent v3.10 database [41]. The ReCiPe 2016 v1.07 impact assessment method, at both midpoint and endpoint levels, has been used [42].

The CA is not developed to attribute the market value of the product, but rather to provide technical tools for understanding the material costs of the FU. This study, therefore, is not possible to understand the full economic value of the product, but only the significant impact of costs of the upstream and core phases. Additionally, data adopted to measure the input/output costs are taken from literature, to guarantee reproducibility of the study. For this reason, the analysis is imprecise and subject to fluctuations in market value. To ensure global accessibility of the data, costs are expressed in USD. CA was conducted by evaluating data obtained from online sources, which were subsequently processed and analyzed using Microsoft Excel. The details of the LCI of the CA are reported in Table S1.

2.2 | Product characteristics

Defined as a monobloc chair with a low backrest, the investigated product is entirely made of PP and additives, weighing 2.6 kg. The materials mixture is reported in Table 1. The monobloc chair is fabricated from a single piece of plastic. The extruded material is inserted into an injection molding unit, enabling the mass production of a large number of pieces from the same machine. This process reduces prices and allows for a convenient, popular market.

2.3 | Life cycle inventory (LCI) for LCA

The primary data, collected in 2024 and referenced to 2023, were provided by a company in Brianza, located north of Milan, that manufactures durable and sustainable outdoor furniture from thermoplastic materials. The company operates automated plants for global distribution. The fundamental processes were derived from all materials associated with the products, using the Ecoinvent v3.10 database. However, it is crucial to also account for uncertainties related to the inventory data itself. As highlighted by recent literature, uncertainties can arise both from intrinsic variability in the data and from the quality and representativeness of the sources used [43].

TABLE 1 Materials mixture of the chair.

Percentage	Material
41.5%	Virgin PP
33%	Recycled PP (R-PP)
24%	Calcium carbonate
1.5%	TiO_2 and carbon black

Upstream phase: This stage involves the extraction and processing of raw materials, whether they are virgin, secondary, or recycled. Additionally, it covers the production of packaging for both raw materials and the finished product, as well as the transportation of materials to the manufacturing facility. The impacts associated with electricity and fuel consumption for product production and transportation are included, along with the treatment of waste and wastewater generated from all upstream activities. The adoption of R-PP was modeled by modifying the Ecoinvent process database entry for *"Polyethylene, high density, granulate, recycled {Europe without Switzerland}| polyethylene production, high density, granulate, recycled | Cut-off, U"*. Specifically, the input process *"Waste polyethylene, for recycling, sorted {Europe without Switzerland}| market for waste polyethylene, for recycling, sorted | Cut-off, U"* was replaced with *"Waste plastic, consumer electronics, sorted {GLO}| market for waste plastic, consumer electronics, sorted | Cut-off, U"*. This adjustment was necessary due to the absence of specific data on PP in the database.

Core phase: this stage encompasses all activities related to the manufacturing of the product at the facility plant and the transport of raw materials to the facility. This includes production, storage, packaging, and other associated manufacturing services such as maintenance operation. Furthermore, this phase encompasses the treatment of waste generated within the facility, as well as the consumption of resources such as electricity, water, and methane throughout the manufacturing process. This stage includes electricity, natural gas, and water consumption within the factory. The maintenance materials, as well as the treatment and disposal of waste generated, are also included. The details of the LCI is reported in Table S2, while the transport features are shown in Table S3.

2.4 | LCA scenarios considered in the analysis

To implement a useful LCA, analyzing the business-as-usual scenario (BAU) is important, but not sufficient. It is recommended to propose multiple mitigative scenarios to enhance the production process from an environmental perspective. In this specific study, to estimate the change in the sustainability of the product, three alternatives' strategies compared to the Business-as-usual (BAU) scenario have been investigated: intervening (i) on energy mix (RES), (ii) on raw materials used (S), and (iii) on both the solutions (BO).

i. RES scenario: this scenario impacts the core phase, substituting, as shown in Table 2, the energy country mix source with energy from photovoltaic panels (PV). The substitution is evaluated at different levels of replacement rate: 25% of PV (RES1), 50% of

TABLE 2 Energy source of control and mitigation scenarios.

Energy origin	BAU [%]	RES1 [%]	RES2 [%]	RES3 [%]	RES4 [%]	BO [%]
Geothermal	0.34	0.28	0.18	0.09	0	0
Hydro	5.30	4.24	2.90	1.40	0	0
Wind power	4.22	3.31	2.30	1.20	0	0
Biomass	2.59	2.18	1.50	0.74	0	0
Photovoltaic	7.50	25	50	75	100	10
Unspecified renewable	0.01	0.01	0.01	0	0	0
Total renewable energy	*19.96*	*35.02*	*56.89*	*78.43*	*100*	*100*
Nuclear	3.80	3.10	2.00	1.00	0	0
Coal	20	16.01	10.88	5.31	0	0
Natural gas	50	40.94	26.71	13.54	0	0
Oil	3.10	2.40	1.80	0.88	0	0
Lignite	0.04	0.03	0.02	0.01	0	0
Unspecified fossil energy	3.10	2.50	1.70	0.83	0	0
Total non-renewable energy	*80.04*	*64.98*	*43.11*	*21.57*	*0*	*0*

Note: All data are reported in percentages. According to the Ecoinvent database, the BAU energy origin refers to the Italian mix in 2023. The tabular data were processed, beginning with the BAU scenario. Consequently, the hypothesized increase in photovoltaic energy was employed to proportion the entire energy mix based on the BAU proportions.

PV (RES2), 75% of PV (RES3), and 100% of PV (RES4). The Ecoinvent database data adopted for this scenario are taken from the dataset titled "*Electricity, low voltage {IT}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off, U*". The use of slanted-roof installation photovoltaic energy was considered the best renewable energy study option, due to the plant location, configuration, and energy availability. Since the RES scenario refers to variations in energy sources, the raw material mix is assumed unchanged and, therefore, equal to the BAU one.

ii. S scenario: this scenario is characterized by the substitution of virgin PP (V-PP) with mechanical recycled PP (R-PP), as shown in Table 3. S1 refers to the use of 100% R-PP, while S2 involves using 50% R-PP in the total PP. Since the S scenario refers to variations in the raw material mix, energy sources are assumed unchanged and, therefore, equal to the BAU ones.
iii. BO scenario: this scenario is proposed as an ideal option, characterized by the use of 100% renewable energy (RES4) and 100% R-PP (S1).

TABLE 3 Input raw material product mix in BAU, S2, and S1.

Material	BAU	S1	S2	BO
Virgin PP	41.50	0.00	37.25	0.00
Recycled PP	33.00	74.50	37.25	74.50
Calcium carbonate	24.00	24.00	24.00	24.00
TiO_2 and carbon black	1.50	1.50	1.50	1.50

3 | RESULTS

3.1 | Environmental profile

The environmental profile of the BAU scenario is reported in Figure 2. In detail, BAU had a total impact of 2.36E + 02 mPt, with 1.78E + 02 mPt (equal to 75.42% of the total) attributed to the upstream part and the core phase, and 5.83E + 01 mPt (equal to 24.58% of the total). The endpoint damage categories are affected with 2.22E + 02 mPt for HH (94.17% of the total), 6.21E + 00 mPt for ES (2.63%), and 7.53E + 00 mPt for RE (3.20%) (Figure 2a). The subdivision between upstream and core phase damage slightly changes, with a higher percentage impact on HH in the core phase. Respectively, HH, ES, and RE are damaged by 1.67E + 02 (94.02% of the total), 4.47E + 00 (2.52% of the total), and 6.16E + 00 mPt (3.46% of the total) in the upstream phase and by 5.52E + 01 (94.85% of the total), 1.75E + 00 (3.00% of the total), and 1.37E + 00 mPt (2.35% of the total) in the core phase. In Figure 2b, the detailed impacts of the upstream and core are visualized. Granulated virgin PP influences by 1.10E + 02 mPt (61.77% of the total upstream phase impact), final packaging by 3.16E + 01 mPt (17.75% of the total upstream phase impact), recycled PP by 1.73E + 01 mPt (9.71% of the total upstream phase impact), and calcium carbonate by 1.22E + 01 mPt (6.85% of the total upstream phase). Total electricity (molding, extrusion, and auxiliary/general) impact represents 74.28% of the total core phase impact, with an overall impact of 58.31 mPt. Transport generates 6.28 mPt (8% of the total core phase impact) and maintenance materials 7.54 mPt (9.61% of the total core phase impact). The midpoint impact categories are reported in Table S4. In terms of GWP, the entire

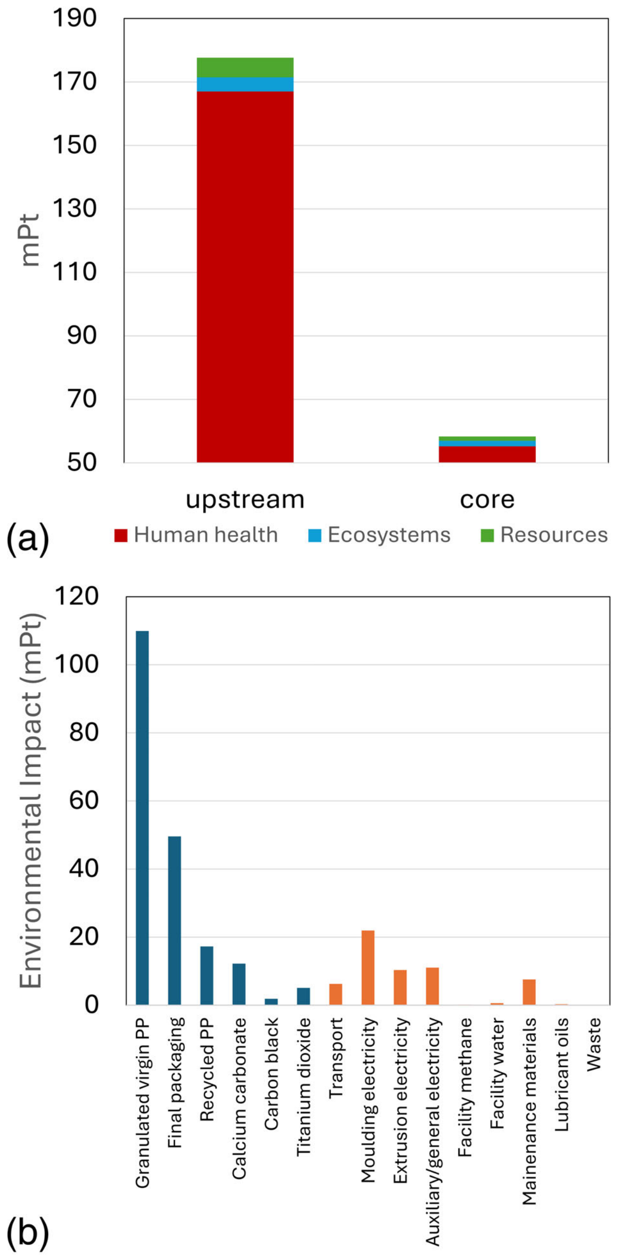

FIGURE 2 Results of business-as-usual scenario. (2) Total damage per endpoint category; (b) Upstream (blue) and core (orange) detailed impacts.

production process has an impact of 2.04E + 00 kg CO2 eq. The FPM data estimate 1.63E-03 kg PM2.5 eq of emission. 5.29E-01 kg 1,4-DCB and 1.67E + 00 kg 1,4-DCB represent, respectively, the impact of HCT and HNCT. The analyzed process generates 1.36E-02 m3 of WC and 1.05E + 00 kg oil eq of FRS.

3.2 | Mitigative scenarios

Total BAU, RES1, RES2, RES3, RES4, S2, S1, and BO damage are, respectively, 2.36E + 02, 2.29E + 02, 2.22E + 02, 2.15E + 02,

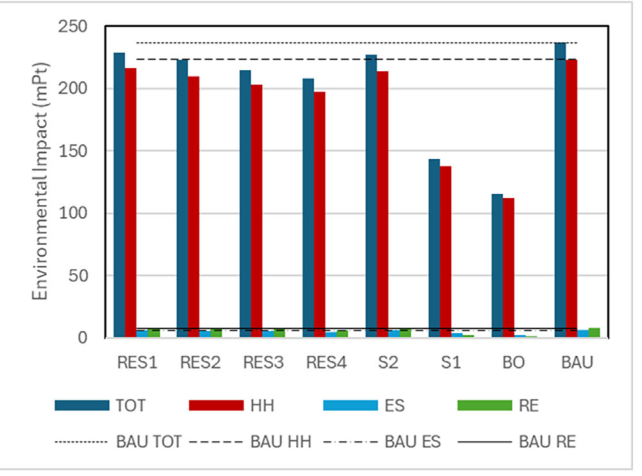

FIGURE 3 Total damage per scenario.

2.08E + 02, 2.27E + 02, 1.43E + 02, and 1.15E + 02 mPt, with a reduction of impact of the −2.9%, −5.9%, −8.9%, −11.9%, −4.1%, −39.6%, and −51.4%, (Figure 3). Regarding S1 and S2 analysis, the total upstream and core impacts are visualized, with a reduction of 5.1% and 49.6% of the BAU upstream impact (from 1.78E + 02 mPt to 1.69E + 02 mPt – S2 and 8.97E + 01 mPt – S1) and of 0.86% and 7.9% of the BAU core impact (from 5.83E + 01 to 5.78E + 01 mPt – S2 and 5.37E + 01 mPt – S1). The HH endpoint damage is reduced from the BAU data, respectively, of the 3.1% (2.16E + 02 mPt – RES1), 5.8% (2.10E + 02 mPt – RES2), 9.0% (2.03E + 02 mPt – RES3), 11.7% (1.97E + 02 mPt – RES4), 4.0% (2.14E + 02 mPt – S2), 38.1% (1.38E + 02 mPt – S1), and 49.8% (1.12E + 02 mPt – BO). The ES endpoint damage is reduced from the BAU data, respectively, of the 4.8% (6.21E + 00 mPt – RES1), 9.7% (5.91E + 00 mPt – RES2), 14.7% (5.30E + 00 mPt – RES3), 19.5% (5.00E + 00 mPt – RES4), 4.4% (5.94E + 00 mPt – S2), 42.2% (3.59E + 00 mPt – S1), and 61.7% (2.38E + 00 mPt – BO). The RE endpoint damage is reduced from the BAU data, respectively, of the 3.6% (7.26E + 00 mPt – RES1), 7.3% (6.98E + 00 mPt – RES2), 10.9% (6.71E + 00 mPt – RES3), 14.5% (6.44E + 00 mPt – RES4), 7.3% (6.98E + 00 mPt – S2), 70.9% (2.19E + 00 mPt – S1), and 85.4% (1.10E + 00 mPt – BO). Regarding the most crucial impact categories, the results for GWP, HCT, HCNT, FPM, and WC are available in Table S4. The impact reduction from BAU of GWP is the 6.4% (RES1), 12.8% (RES2), 19.2% (RES3), 25.6% (RES4), 4.7% (S2), 45.7% (S1), and 71.5% (BO). HCT is reduced from the BAU data, respectively, to 0.16% (RES1), 0.32% (RES2), 0.48% (RES3), 0.64% (RES4), 3.4% (S2), 32.9% (S1), and 33.5% (BO). HNCT is increased from the BAU data, respectively, of the 1.8% (RES1), 3.5% (RES2), 5.3% (RES3), 7.1% (RES4), 2.2% (S2), 21.2% (S1), and 14.2% (BO). FPM is reduced from the BAU data, respectively, by 2.9% (RES1), 5.8% (RES2), 8.7% (RES3), 11.6% (RES4), 4.0% (S2), 38.6% (S1), and 50.1% (BO). WC is reduced from the BAU data, respectively, by 2.3% (RES1), 4.7% (RES2), 7.0% (RES3), 9.4% (RES4), 6.5% (S2), 63.7% (S1), and 73.1% (BO).

3.3 | Cost analysis (CA)

i. To facilitate a comprehensive evaluation of the CA results, the inquiries presented in Section 2.3 are addressed. Which is the most expensive phase of the analysis?
ii. Figure 4a represents the average cost for the FU divided by upstream and core phases. The proposed graph takes into account market price fluctuations. To manufacture a chair, 1.44 USD is needed. 71.6% of the costs are related to the upstream phase. Therefore, the most expensive phase of the analysis is the upstream one. Which material or process generates a higher cost for each phase?

Figure 4b represents the average costs of materials and processes for the upstream and core phases. The higher costs per phase are due, respectively, to virgin and recycled PP, as well as facility electricity. Approximately 50.4% of the upstream phase cost is attributable to virgin PP (1.40 USD/chair) and 33.0% to recycled PP (0.92 USD/chair). 82.5% of the core phase cost is attributable to facility electricity (0.78 USD/chair). Percentage analysis of price fluctuation reveals high price variation (>30%) for most raw material inputs and packaging products, specifically: Granulated Virgin PP, with a variation of 55.5%; Recycled PP, at 33.6%; and overall packaging, at 77.4%.

4 | DISCUSSION

This paper is pioneering in its analysis of the impacts of combining energy inputs and introducing different raw materials in the production process. The substantial 51.2% reduction in impact is predominantly attributable to the substitution of 76.8% of all PP inputs with recycled PP. The use of sustainable energy sources, such as photovoltaics, is crucial for reducing environmental impacts. However, it is worth noting that modifying the energy mix alone is insufficient for achieving this objective. A key to achieving a more sustainable process is the prioritization of raw materials with a lower impact. However, this may present challenges not so much in terms of cost, given that the cost of virgin and recycled PP is similar (Table S1), but rather in the chemical, physical, and mechanical properties of the materials. While substituting raw materials is the most effective strategy, it also requires significant R&D and plant redesign costs. The use of recycled materials, while undoubtedly more sustainable, is hindered by the need to ensure their quality and adapt production facilities, which represent significant challenges. Recycled polypropylene (rPP) often shows reduced performance compared to virgin PP (vPP): tensile strength may decrease from ~35 MPa to ~26 MPa, and elongation at break from over 400% to below 100% [44,45].

The use of renewable electricity is a more easily implementable alternative that does not require redesigning the production system or altering the final product. However, installing photovoltaic panels increases specific environmental impacts, such as TEX (+3.07% from BAU to RES4), MEX (+21.2% from BAU to RES4), FEX (+25.3% from BAU to RES4), HNCT (+6.59% from BAU to RES4), and MRS (+4.96% from BAU to RES4), derived from extraction, refinement, and decommissioning activities, as shown in Table S4. Although increases in certain midpoint impact factors are observed, the endpoint analysis demonstrates that the overall benefits of photovoltaic (PV) implementation outweigh the potential risks associated with individual impact categories (−11.9%).

In this study, the clear reduction in impacts from BAU to BO is consolidated by equally significant reductions in specific impacts, such as the 71.3% reduction in GWP, comparable to the 55% reduction achieved by Yahyapour et al. [32], which replaces virgin PP with PP derived from waste.

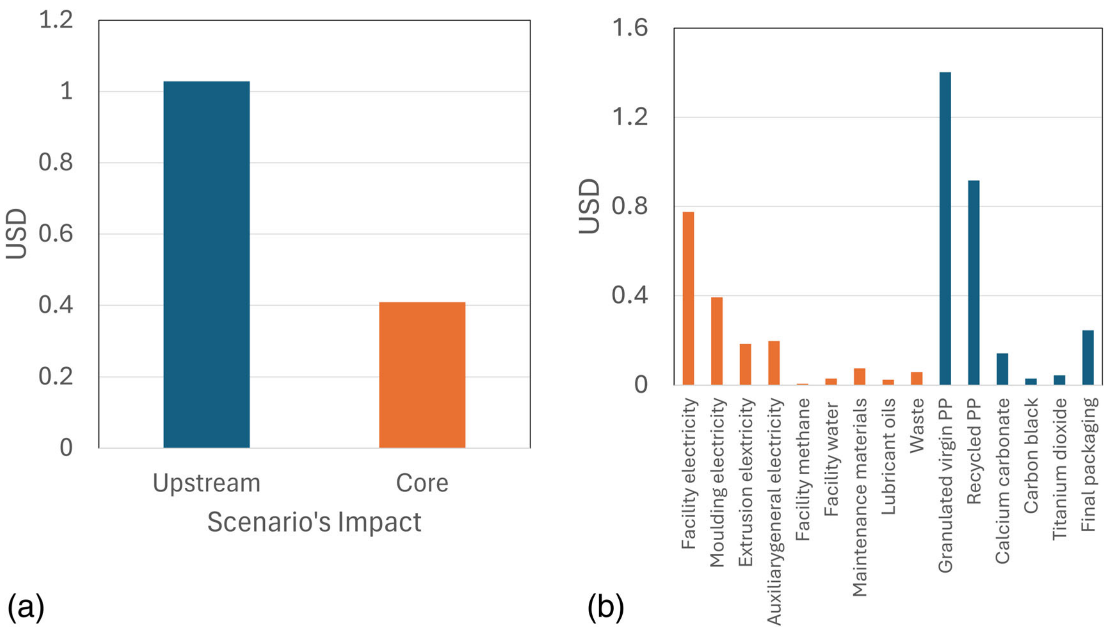

FIGURE 4 CA graphs. (a) Total damage per scenario; (b) Upstream (blue) and core (orange) phases' average cost.

Regarding the chair cost impacts, the raw material cost (virgin or recycled) drives the overall cost, accounting for 73.2% of the total price (1.44 USD/chair). Electricity is also crucial due to the dependency on electrically operated machinery in the process. The exploitation of self-generated renewable energy, which is free from external costs once the costs of implementing the plant have been amortized, could represent an optimal solution to mitigate the costs of the phase itself. The high fluctuation of prices suggests instability in production and transportation costs, or due to supply and demand dynamics.

As this work is pioneering in its field, further analysis could be carried out in future studies. For instance, the assessment of photovoltaic (PV) energy could be integrated with analyses of green certificates, alternative energy trading, and energy mixes. In addition to LCA and CA, the potential for S-LCA evaluation should be explored [46,47].

To ensure possible future development, it is important to note the following limitations and assumptions of the study. The LCA carried out focuses exclusively on a single product; conducting an LCA of the entire company could provide a more comprehensive view of its overall environmental impact and allow for a comparison with the specific impact of the chair. Moreover, the current LCA only considers the materials used in the process. In this regard, a Consequential LCA (CLCA) could be beneficial for evaluating alternative environmental impact scenarios by analyzing different raw material solutions, varying percentage combinations, and the use of different industrial machines. The analysis also takes into account only black and white chairs, as these represent the main production of the company; however, assessing the variation in environmental impact due to color differences and the presence of different additives, even if minimal, would be of interest. In addition, the research evaluated the environmental and economic implications of alternative input materials and renewable energy sources. A logical next step could be the implementation of a more accurate multi-criteria decision analysis, which would allow the simultaneous assessment of cost, environmental impact, and durability for each alternative considered. Further developments could also include an uncertainty analysis of the LCA, for instance using Monte Carlo simulations in SimaPro, to verify the robustness of the results and account for data variability; such an approach would help identify the most influential parameters and increase the reliability of impact estimates. Finally, a sensitivity analysis of the economic data could be carried out to determine how fluctuations in raw material and energy market prices might influence cost stability and the resilience of the overall system.

5 | CONCLUSION

The LCA and CA study of FU has yielded key insights into impact reduction. The incoming raw material's impact is predominant compared to energy supply, with critical peaks in GWP, HCT, HNCT, and FPM. Adopting recycled raw materials and renewable energy can cut environmental impacts by up to 51.2%, with the upstream phase driving 75.3% of the BAU total impact, showing a significant environmental benefit compared to granulated virgin PP and the use of the conventional Italian energy mix. Economically, the upstream phase also dominates costs, emphasizing the importance of the raw materials market.

This study offers decision-makers valuable guidance on implementing polypropylene plants, promoting sustainability and a circular economy. This research demonstrates that alterations in the production and utilization of resources can, under certain technical feasibility conditions, guarantee a substantial decrease in environmental impacts, while concurrently assigning a nearly constant economic value to virgin substitute raw materials.

These findings serve as a foundational starting point for critical and constructive analysis of the industrial process system, as well as for initiating discussions and research in the field of optimizing recycled thermoplastics as substitutes for virgin materials. Advancing these prerogatives supports the achievement of Sustainable Development Goals, particularly SDG 3 (health), SDG 11 (sustainable cities and communities), and SDG 13 (climate action).

AUTHOR CONTRIBUTIONS

Lucrezia Maggi: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Alberto Pietro Damiano Baltrocchi**: Conceptualization, Validation, Methodology, Writing review and editing, Visualization. **Marco Carnevale Miino**: Validation, Methodology, Writing review and editing, Visualization. **Elena Cristina Rada**: Validation, Methodology, Writing review and editing. **Vincenzo Torretta**: Conceptualization, Validation, Project administration, Supervision. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study is included in this published article.

ORCID

Lucrezia Maggi https://orcid.org/0009-0003-2308-2467
Alberto Pietro Damiano Baltrocchi https://orcid.org/0000-0002-8822-5866
Marco Carnevale Miino https://orcid.org/0000-0003-3669-1635
Elena Cristina Rada https://orcid.org/0000-0003-0807-1826
Vincenzo Torretta https://orcid.org/0000-0002-7594-1169

REFERENCES

1. Marsh K, Bugusu B. Food packaging—roles, materials, and environmental issues. *J Food Sci*. 2007;72:R39-R55. doi:10.1111/j.1750-3841.2007.00301.x

2. Park JH, Koo MS, Cho SH, Lyu M-Y. Comparison of thermal and optical properties and flowability of fossil-based and bio-based polycarbonate. *Macromol Res*. 2017;25:1135-1144. doi:10.1007/s13233-017-5153-2
3. EPA. About Plastic Products and Plastic Pollution. [WWW Document]. United States Environmental Protection Agency. 2024 https://www.epa.gov/plastics/about-plastic-products-and-plastic-pollution (accessed 3.19.25)
4. Plastic Europe. Plastics The Facts 2021. 2021.
5. EEA. Plastics [WWW document]. European Environmental Agency Website. 2024 https://www.eea.europa.eu/en/topics/in-depth/plastics (accessed 3.19.25)
6. Baltrocchi APD, Maggi L, Carnevale Miino M, Torretta V, Rada EC. Comparison of mixed and door-to-door Systems for Urban Waste Collection in terms of effectiveness and greenhouse gas emissions: a case study from two mountainous Italian valleys. *Resources*. 2024b;13:17. doi:10.3390/resources13010017
7. Hurley R, Horton A, Lusher A, Nizzetto L. Plastic waste in the terrestrial environment. *Plastic Waste and Recycling: Environmental Impact, Societal Issues, Prevention, and Solutions*. Academic Press; 2020. doi:10.1016/B978-0-12-817880-5.00007-4
8. Wan Y, Wu C, Xue Q, Hui X. Effects of plastic contamination on water evaporation and desiccation cracking in soil. *Sci Total Environ*. 2019;654:576-582. doi:10.1016/j.scitotenv.2018.11.123
9. Williams AT, Rangel-Buitrago N. Marine litter: solutions for a major environmental problem. *J Coast Res*. 2019;35:648-663. doi:10.2112/JCOASTRES-D-18-00096.1
10. Erickson E. Shaping a federal strategy for chemical recycling: moving toward sensible applications of emerging technologies in US plastic waste management. *Environ Prog Sustain Energy*. 2024;43(1):e14333. doi:10.1002/ep.14333
11. Nayanathara Thathsarani Pilapitiya PGC, Ratnayake AS. The world of plastic waste: a review. *Clean Mater*. 2024;11:100220. doi:10.1016/j.clema.2024.100220
12. Hosseini A. Theoretical assessment of the environmental impact of the preheating stage in thermoplastic composite processing: a step toward sustainable manufacturing. *J Manuf Mater Process*. 2024;8:120. doi:10.3390/jmmp8030120
13. Mărieş GRE, Abrudan AM. Thermoplastic polymers in product design. *IOP Conf Ser Mater Sci Eng*. 2018;393:12118. doi:10.1088/1757-899X/393/1/012118
14. Baltrocchi APD, Carnevale Miino M, Maggi L, Rada EC, Torretta V. A comprehensive critical review of life cycle assessment applied to thermoplastic polymers for mechanical and electronic engineering. *Environ Technol Rev*. 2025a;14:458-470. doi:10.1080/21622515.2025.2491632
15. Shen M, Huang W, Chen M, Song B, Zeng G, Zhang Y. (micro)plastic crisis: un-ignorable contribution to global greenhouse gas emissions and climate change. *J Clean Prod*. 2020;254:120138. doi:10.1016/j.jclepro.2020.120138
16. Patel K, Vashist M, Goyal D, Sarma R, Garg R, Singh SK. From waste to resource: a life cycle assessment of biochar from agricultural residue. *Environ Prog Sustain Energy*. 2025;44(2):e14558. doi:10.1002/ep.14558
17. Longo C, Savaris M, Zeni M, Brandalise RN, Grisa AMC. Degradation study of polypropylene (PP) and bioriented polypropylene (BOPP) in the environment. *Mater Res*. 2011;14:442-448. doi:10.1590/S1516-14392011005000080
18. Freudenthaler PJ, Fischer J, Liu Y, Lang RW. Polypropylene post-consumer Recyclate compounds for thermoforming packaging applications. *Polymers (Basel)*. 2023;15:345. doi:10.3390/polym15020345
19. Siracusa V, Blanco I. Bio-polyethylene (bio-PE), bio-polypropylene (bio-PP) and bio-poly(ethylene terephthalate) (bio-PET): recent developments in bio-based polymers analogous to petroleum-derived ones for packaging and engineering applications. *Polymers (Basel)*. 2020;12:1641. doi:10.3390/polym12081641
20. Galve JE, Elduque D, Pina C, Javierre C. Life cycle assessment of a plastic part injected with recycled polypropylene: a comparison with alternative virgin materials. *Int J Precis Eng Manuf-Green Technol*. 2022;9:919-932. doi:10.1007/s40684-021-00363-2
21. Calleja D. Why the "new plastics economy" must be a circular economy. *Field Actions Sci Rep*. 2019;19:22-27.
22. Baltrocchi APD, Carnevale Miino M, Katsoyiannis IA, et al. Assessment of environmental sustainability of drinking water treatments for arsenic removal. *Resour Conserv Recycl*. 2024a;211:107878. doi:10.1016/j.resconrec.2024.107878
23. Dal Lago B, Krelani V, Visconti D, Berisha E, Baltrocchi APD, Torretta V. Comparison of the Environmental Impact of Similar Prefabricated Industrial Structures Made of Precast Concrete or Steel. 161–168 2025. doi:10.1007/978-3-031-80672-8_20
24. Ferronato N, Baltrocchi APD, Romagnoli F, Calle Mendoza IJ, Gorritty Portillo MA, Torretta V. Environmental life cycle assessment of biomass and cardboard waste-based briquettes production and consumption in Andean areas. *Energy Sustain Dev*. 2023;72:139-150. doi:10.1016/j.esd.2022.12.005
25. ISO. ISO 14040 Environmental Management—Life Cycle Assessment—Principles and Framework. Geneva, Switzerland. 2006a.
26. ISO. ISO 14044 Environmental Management—Life Cycle Assessment—Requirements and Guidelines. Geneva, Switzerland. 2006b.
27. Baltrocchi APD, Lotti D, Carnevale Miino M, Maggi L, Rada EC, Torretta V. Environmental impact of three different engineering thermoplastics: how much does it change when using recycled polyamide? *J Clean Prod*. 2025b;514:145769. doi:10.1016/j.jclepro.2025.145769
28. Cui X, Zhao Y, Guo X, Huo L, Li D. Multi-indicators environmental impact analysis of takeaway lunch boxes based on life cycle assessment. *Environ Res*. 2025;265:120458. doi:10.1016/j.envres.2024.120458
29. Zhao F, Liu X, Feng T, Zhao J, Guo W. Forming performance and environmental impact of bamboo fiber reinforced polypropylene composites based on injection molding process for automobiles. *Polym Compos*. 2025;46:567-578. doi:10.1002/pc.29008
30. Li W, Feng T, Lu T, et al. Optimisation of compression molding parameters and lifecycle carbon impact assessment of bamboo fiber-reinforced polypropylene composites. *Polymers*. 2024;16:3435. doi:10.3390/polym16233435
31. Skinner C, Jawaid M, Singh B, et al. Life cycle assessment of pulp-moulded and thermoformed oil palm fibre-based food tray. *Discover Appl Sci*. 2024;6:1-12. doi:10.1007/s42452-024-06335-w
32. Yahyapour R, Baskan-Bayrak H, Yagcı YE, Saner Okan B. Co-reinforcing sustainable graphenes from thermoset/thermoplastic wastes for enhanced polypropylene matrix composites in automotive engineering. *Polym Compos*. 2024;45:14146-14161. doi:10.1002/pc.28760
33. Ansari Movahed D, Jonoobi M, Ashori A, Mekkonen TH. Life cycle assessment and mechanical properties of nanocomposites based on cellulose nanocrystals. *Polym Eng Sci*. 2023;63:1752-1760. doi:10.1002/pen.26321
34. Bakshi P, Pappu A, Bharti DK, Parmar B, Patidar R, Srivastava AK. Life cycle assessment of calcium-rich industrial waste reinforced polypropylene and low-density polyethylene composites using the cradle-to-gate approach. *ACS Sustain Chem Eng*. 2022;10:13710-13721. doi:10.1021/acssuschemeng.2c03751
35. Mannheim V. Life cycle assessment model of plastic products: comparing environmental impacts for different scenarios in the production stage. *Polymers (Basel)*. 2021;13:777. doi:10.3390/polym13050777
36. Deng Y, Guo Y, Wu P, Ingarao G. Optimal design of flax fiber reinforced polymer composite as a lightweight component for

automobiles from a life cycle assessment perspective. *J Ind Ecol*. 2019;23:986-997. doi:10.1111/jiec.12836

37. Korol J, Burchart-Korol D, Pichlak M. Expansion of environmental impact assessment for eco-efficiency evaluation of biocomposites for industrial application. *J Clean Prod*. 2016;113:144-152. doi:10.1016/j.jclepro.2015.11.101
38. EPD. Plastic in primary forms (No. 4.0.0). Stockholm. 2024.
39. Huijbregts MAJ, Steinmann ZJN, Elshout PMF, et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess*. 2017;22:138-147. doi:10.1007/s11367-016-1246-y
40. SimaPro. SimaPro [WWW Document]. PRé Sustainability B.V. 2025 https://simapro.com/new-release-simapro-craft-10-1/#new (accessed 3.19.25)
41. Ecoinvent. Ecoinvent [WWW Document]. 2025 https://support.ecoinvent.org/ecoinvent-version-3.10 (accessed 3.19.25)
42. Hauschild MZ, Goedkoop M, Guinée J, et al. Identifying best existing practice for characterisation modeling in life cycle impact assessment. *Int J Life Cycle Assess*. 2013;18:683-697. doi:10.1007/s11367-012-0489-5
43. Tan ECD, Tu Q, Martins AA, Yao Y, Sunol A, Smith RL. Uncertaintly in inventories for life cycle assessment: state-of-the-art, challenges, and new technologies. *Environ Prog Sustain Energy*. 2025;44(4):1-11. doi:10.1002/ep.14644
44. Barbosa LG, Piaia M, Ceni GH. Analysis of impact and tensile properties of recycled polypropylene. *Int J Mater Eng*. 2017;7(6):117-120. doi:10.5923/j.ijme.20170706.03
45. Demets R, Van Kets K, Huysveld S, Dewulf J, De Meester S, Ragaert K. Addressing the complex challenge of understanding and quantifying substitutability for recycled plastics. *Resour Conserv Recycl*. 2021;174:105826. doi:10.1016/j.resconrec.2021.105826
46. Baltrocchi APD, Ferronato N, Calle Mendoza IJ, Gorritty Portillo MA, Romagnoli F, Torretta V. Socio-economic analysis of waste-based briquettes production and consumption in Bolivia. *Sustain Prod Consum*. 2023;37:191-201. doi:10.1016/j.spc.2023.03.004
47. Traverso M, Bell L, Saling P, Fontes J. Towards social life cycle assessment: a quantitative product social impact assessment. *Int J Life Cycle Assess*. 2018;23:597-606. doi:10.1007/s11367-016-1168-8

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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